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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Applicant:	Davor PROTIC et al.
Title:	POSITION-SENSITIVE GERMANIUM DETECTORS HAVING A MICROSTRUCTURE ON BOTH CONTACT SURFACES
Appl. No.:	10/511,734
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Examiner:	Shun K. Lee
Art Unit:	2884
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DECLARATION UNDER 37 C.F.R. § 1.132

1. I, Davor Protic, do hereby declare as follows.

2. I am a co-inventor named in the captioned application, and was employed 38 years by the current assignee of the application up to 30.April 2007. Since 1.Mai 2007 I have been a pensioner.

3. I have a Master of Science degree in Solid State Physics given from the University of Zagreb, Croatia.

4. I have more than 30 years of experience developing semiconductor-based position sensitive detectors for charged particles or photons.

5. At the time the present application was originally filed, it was well-known that a detector comprising a Boron doped contact was a durable detector with an excellent energy resolution in the measurement. This is still true today.

6. As evidence of this, I have attached as exhibit 1 a Web-site print out from www.ortec-online.com. Ortec is a well-known producer and seller of corresponding detectors. As shown in the Web site in the bullet points near the top of the first page, ORTEC

is using a Boron ion implanted outer contact. According to the Ortec-document, the contact is "ultra stable". A corresponding detector shows a lot of excellent properties.

7. The following features are of most interest with regard to a detector in the field of the application: (1) of importance is the accuracy in the energy measurement; (2) of importance is to provide a detector with a good energy resolution in the measurement; (3) of importance is to provide a durable detector; and (4) it is often of importance to provide a detector with a good positional resolution.

8. However, a person skilled in the art is never interested in improving detector blocking contacts, since such detectors, in the commercial marketplace, do not need better blocking contacts.

9. Detectors in the commercial marketplace do not need better blocking contacts because, in the typical operating environment, better blocking contacts would not increase the energy resolution. The energy resolution of a detector depends on many factors. One factor is the leakage current of a detector. The leakage current of a detector depends on the operating temperature and the blocking contact.

10. The leakage current of a detector is small if the operating temperature is low. This is especially true for detectors made of Germanium. The typical operating temperature of a detector made of Germanium is 77 K and consequently low. As a result, the leakage current is low. Under these circumstances, it is therefore not possible to increase the energy resolution in the measurement by providing better blocking contacts. Thus, a person skilled in the art is especially not interested in better blocking contacts.

11. Furthermore, there is really no motivation to replace Boron as a contact. As stated at the bottom of page 4 and the top of page 5 of our application, experiments have been performed by other groups to provide amorphous Germanium contacts. In these experiments, a structured metal layer sits on top of amorphous Germanium. The structure of the metal layer, however, was not carried through to the amorphous Germanium layer. The results of these experiments showed that a relatively poor energy resolution was achieved, and that a large number of measurement errors occurred.

12. A person of skill in the art would have known this at the time the application was filed, and therefore would have believed that replacing the Boron contact with an amorphous Germanium contact would yield a poor energy resolution. It was surprising to discover, on the other hand, that continuing the structure of the metallic layer through the amorphous Germanium layer into the crystalline bulk Germanium actually improved the energy resolution above that of unstructured amorphous Germanium layer(as described at point 11).

13. I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements are made with knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title XVIII of the United States Code and that willful false statements may jeopardize the validity of this Application for Patent or any patent issuing thereon.

Dated: 21. January 2008

Davor Protic

Davor Protic

Exhibit 1

to Declaration of Davor Protic

Detector Element

GAMMA-X Germanium (HPGe) Coaxial Detectors
(in PopTop Capsule or Streamline Cryostats)

For Compton-suppressed gamma spectroscopy, for measurements involving spectroscopy over the widest energy range, and in any situation where neutron da is likely.

- Efficiencies to over 100%
- PopTop flexibility
- Spectroscopy from 3 keV to 10 MeV
- ULTRA thin, ultra stable boron ion implanted outer contact
- High resistance to neutron damage
- Customer-repairable for neutron damage (option)
- Excellent timing characteristics
- Ideal for Compton-suppressed gamma spectroscopy
- Be window supplied with protective cover; Al or carbon fiber window option available additional charge
- High-rate indicator
- PLUS preamplifier option for ultra-high-rate applications
- Automatic high-voltage shutdown protects preamplifier input FET

The GAMMA-X detector is a coaxial Germanium (Ge) detector with an ultra-thin entrance wir While most coaxial detectors have entrance windows from 500- to 1000-μm thick, the entrai window of the GAMMA-X detector is a 0.3-μm-thick, ion-implanted contact. Ion implantation results in a totally stable contact which will not deteriorate with repeated cycling.

Figure 8 compares ORTEC's GAMMA-X and GEM detector elements. The GAMMA-X detector element depicted is different from that of the GEM detector because the former's starting mi is n-type germanium.

The GAMMA-X detector is the only Ge spectrometer designed for both gamma- and x-ray spectroscopy with high precision and efficiency for both. This point can be illustrated by com the GAMMA-X detector with a LEPS and with an HPGe coaxial detector (Fig. 9). The GAMMA- detector offers a combination of the performance of the LEPS at low energies and a coaxial detector at high energies.

High- and Low-Energy Performance of the GAMMA-X Detector

The high-energy performance of a GAMMA-X detector is defined by its relative efficiency, resolution, and peak-to-Compton ratio at ^{60}Co.

The low-energy performance of this detector is defined by its resolution at 5.9 keV, its active surface area, and the detector window thickness.

The thickness of the entrance contact of the GAMMA-X detector is described by the ratio of t areas of two peaks of a readily available source. The peaks chosen are those of the 88-keV

gamma rays from the ^{109}Cd and of the 22.16-keV Ag K x rays from the same source. The warranted window attenuation ratio

$$W_E = \frac{\text{peak area at 22.16 keV}}{\text{peak area at 88 keV}}$$

is 20. Obviously, the ability to see and measure the resolution accurately at 5.9 keV speaks eloquently of the thinness of the entrance window.

Figures 10–12 show a comparison of the low-energy performance of a GEM HPGe coaxial de (Fig. 10), a 5-cm active area, 10-mm-deep LEPS (Fig. 11), and a GAMMA-X detector (Fig. 1;

In the GEM coaxial detector the thick (~700 µm) lithium-diffused outer contact completely a the Ag K x rays of the ^{109}Cd source (Fig. 10). Only the 88-keV gamma-ray line is visible. In GAMMA-X detector, the entrance window of the detector element itself is 0.3 µm thick. The rays are perfectly visible, with excellent peak-to-valley ratios (Fig. 12). The very low-energy escape peaks in Fig. 12 are totally missing in Fig. 10. Figure 11 shows the spectrum as obtai with an HPGe detector expressly designed for work at energies below 100 keV: a 5-cm activ area, 10-mm-deep LEPS. The spectra of Figs. 11 and 12 are quite similar.

Beryllium Window

Detectors supplied with 2-3/4-in.-diam endcaps (10 to ~35%) are supplied with 2-in.-diam I windows; those supplied in 3-1/4-in.-diam endcaps (~30 to 65%) are supplied with 2-1/2-ir diam Be windows. These windows are 0.020 in. thick and have a transmission coefficient of at 5.9 keV. (Low-background carbon fiber windows are optional. See Figure 22 for transmiss characteristics of the Be and carbon fiber windows.) Detectors in 3-3/4-in.-diam. endcaps (~ 100%) receive 3.3-in.-diam. Be windows which are 0.030 in. thick.

Guaranteed Performance at 5.9 keV

To achieve good energy resolution at 5.9 keV, the technology of this state-of-the-art detectc must be well understood by the manufacturer. Resolution specifications stated only at 14 or keV can be misleading and may be indicative of having failed to master the technology.

High-Voltage Shutdown and High-Rate Indicator

GAMMA-X detectors have high-voltage shutdown and high-rate indicator protection features. LN_2 supply is exhausted and the detector begins to warm while high-voltage bias is applied (using the Model 659 Bias Supply), the high voltage automatically shuts off, thus protecting t FET from damage.

This is accomplished with a temperature sensor (located on the mount behind the detector) shuts down the high voltage before the molecular sieve can outgas and cause a dangerous h voltage arc. Using the high-leakage current of a warming detector to shut down the high vol can result in FET and detector damage.

Neutron Damage Resistance

In the GEM detector, in which the outer contact is positively biased, hole collection dominate charge collection process; in the GAMMA-X detector, electron collection is the dominant proc

Fast neutrons generate hole-trapping centers; that is, negatively charged defects that trap h but not electrons.

Therefore, the GAMMA-X detector, in which the hole collection process is of secondary impor is basically less sensitive to radiation damage than coaxial Ge devices in which the hole colle process is of primary importance. These theoretical considerations have been experimentally confirmed.[2]

Figure 13, a plot of the 1.33-MeV FWHM resolution as a function of fast neutron fluence for t GAMMA-X and a GEM detector of the same efficiency, shows that the GAMMA-X detector is fa more resistant to fast neutron radiation damage.[2] As noted, the detector temperature affects radiation damage resistance to fast neutrons.

It should be noted that **once severe radiation damage has occurred**, the "longest mileag obtained by avoiding cycling the detector to room temperature.[3] This is true for either p- or Ge detectors. However, for slightly damaged GAMMA-X detectors (~0.1 keV degradation), cy or even leaving the detector warm for an extended period, will have no unfavorable effect.[4]

GAMMA-X detectors should be maintained at a temperature as close to 77 K as possible to minimize the extent of radiation damage. Therefore a streamline cryostat, with one less ther connection, is a better choice than a PopTop for this purpose.

Customer-Neutron-Damage-Repairable Detectors

Repair of neutron-damaged GAMMA-X detectors can be performed at any of our worldwide r facilities, or by you in your own laboratory. Contact us for information about our Customer- Neutron-Damage-Repairable GAMMA-X detectors.

Options of Interest

- PLUS preamplifier option for ultra-high-rate applications.
- Carbon fiber window or all-aluminum endcap — on request, no additional charge.
- Non-PopTop low-background versions of the GAMMA-X detector are available.
- X-COOLER II option for practical LN2-free cooling.

Ordering Information

GAMMA-X Germanium (HPGe) Coaxial Detector* (Non-PopTop or PopTop)
For GMX Detector in PopTop capsule, add "P4" to the model no. [e.g., GMX10P4-70]
Endcap diameter must be specified, see Endcap Diameter Options [e.g., GMX10-70, GMX35P4-76]
FW.02M/FWHM Specification is Typical, NOT Warranted

Model No.	Relative Photopeak Efficiency (%)	Resolution @5.9 keV (eV FWHM)	Resolution @1.33 MeV (keV FWHM)	Peak-to-Compton Ratio	Peak Shape† FW.1M/ FWHM	Peak Shape† FW.02M/** FWHM	End Diam Opti
GMX10	10	600	1.80	40:1	1.9	2.6	-7
GMX15	15	635	1.85	44:1	1.9	2.6	-7
GMX20	20	650	1.90	48:1	1.9	2.8	-7
GMX25	25	690	1.90	48:1	1.9	2.8	-70, -7

GMX30	30	715	1.90	52:1	1.9	2.8	-70, -7
GMX35	35	730	1.95	55:1	2.0	3.0	-70, -7
GMX40	40	760	1.95	59:1	2.0	3.0	-76,
GMX45	45	800	2.0	60:1	2.0	3.0	-76,
GMX50	50	800	2.2	58:1	2.0	3.0	-8
		(keV FWHM)					
GMX60	60	1.10	2.3	56:1	2.0	3.0	-83,
GMX70	70	1.10	2.3	60:1	2.0	3.0	-9
GMX80	80	1.10	2.3	63:1	2.0	3.0	-9
GMX90	90	1.20	2.4	64:1	2.1	3.1	-9
GMX100	100	1.20	2.5	64:1	2.2	3.2	-9
Options							
-A	For PopTop Capsule with 1.3 mm thick Al Window, add "-A" to the model no. [e.g., GMX90P4-95-A] (see Table 3 for transmission data)						
-C	Carbon Fiber Window (see Figure 22 for transmission data)						
-RB	Reduced Background PopTop Capsule with Carbon Fiber Endcap, add "-RB" to the model numbe GMX90P4-95-RB]						
-RB-B	Reduced background PopTop capsule with Be Window in Cu Endcap, add "-RB-B" to the model n [e.g., GMX10P4-95-RB-B]						
-PLUS	Ultra-high-count-rate Preamplifier, add "-PLUS" to the model number [e.g., GMX90P-95-PLUS for PopTop or GMX90-95-PLUS for Non-PopTop]						
SMART-1-N	SMART-1 detector option for negative bias detector. To order, add SMART-1-N as a separate lin						

*All GAMMA-X PopTop detector capsules include sealed detector element, preamplifier, high-voltage filter, and a Be window 0.02 inches thick and with diameter ⩾ that of the detector element. Useful energy range is 3 keV to 10 MeV.

†FWHM = Full Width at Half Maximum; FW.1M = Full Width at One-Tenth Maximum; FW.02l Full Width at One-Fiftieth Maximum; total system resolution for a source at 1000 counts/s measured in accordance with ANSI/IEEE Std. 325-1996, using ORTEC standard electronics.

**Typical Value. Specification is in eV for efficiencies <60% and thereafter in keV.

NOTE: For those familiar with HPGe detector specifications, you will notice that ORTEC now ONLY "first category" detector specifications. Recent process improvements now make this possible.

2R.H. Pehl, N.W. Madden, J.H. Elliott, T.W. Raudorf, R.C. Trammell, and L.S. Darken, Jr., "Radiation Damage Resistance of Reverse Electrode Ge Coaxial Detectors," *IEEE Trans. Nucl. Sci.* **NS**-26, N1, 321–23 (1979).

3H.W. Kraner, R.H. Pehl, and E.E. Haller, "Fast Neutron Radiation Damage of High-Purity Germanium Detecto *IEEE Trans. Nucl. Sci.* **NS**-22, N1, 149 (1975).

4T.W. Raudorf, R.C. Trammell, and Sanford Wagner, "Performance of Reverse Electrode HPGe Coaxial Detect Light Damage by Fast Neutrons," *IEEE Trans, Nucl. Sci.* **NS**-31, N1, 253 (1984).

Attachment 2

M. Amman, P.N. Luke, S.E. Boogs, NUCLEAR INSTRUMENTS AND METHODS IN PHYSICS RESEARCH A 579 (2007) 886-890

Available online at www.sciencedirect.com

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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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Amorphous-semiconductor-contact germanium-based detectors for gamma-ray imaging and spectroscopy ☆

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Abstract

Germanium-based detectors are the standard technology used for gamma-ray spectroscopy when high efficiency and excellent energy resolution are desired. By dividing the electrical contacts on these detectors into segments, the locations of the gamma-ray interaction events within the detectors can be determined as well as the deposited energies. This enables simultaneous gamma-ray imaging and spectroscopy and leads to applications in the areas of astronomy, nuclear physics, environmental remediation, nuclear nonproliferation, and homeland security. Producing the fine-pitched electrode segmentation often required for imaging has been problematic in the past. To address this issue, we have developed an amorphous-semiconductor contact technology. Using this technology, fully passivated detectors with closely spaced contacts can be produced using a simple fabrication process. The current state of the amorphous-semiconductor contact technology and the challenges that remain are given in this paper.

PACS: 07.85.Nc; 29.40.Gx; 29.40.Wk; 95.55.Ka

Keywords: Gamma-ray imaging; Gamma-ray spectroscopy; Germanium detector; Orthogonal strip; Position sensing

1. Introduction

There are several advantages for choosing high-purity Ge for gamma-ray spectroscopy. These include (1) commercial availability of large detector volumes (10 cm diameter boules), (2) ability to fully deplete thick detector layers (> 1 cm), (3) relatively high atomic number, (4) near-perfect charge collection, and (5) favorable charge generation statistics. The first three advantages lead to high detection efficiency and the latter two to excellent energy resolution (<0.2% FWHM at 1.33 MeV). However, because of the small bandgap energy of Ge, the detectors do require cryogenic cooling (to near 100 K) in order to reduce the thermal generation of electron–hole pairs that tend to obscure the small signal current generated by the gamma-ray interactions.

Combining gamma-ray imaging with spectroscopy forms a powerful tool for basic scientific research and practical radioisotope detection and characterization. Gamma-ray imaging often relies on detectors that can accurately determine the location of the gamma-ray interaction events within the detector volumes as well as the deposited energies [1]. The development of high spectroscopic performance Ge-based imaging instruments has been hampered in the past by difficulties in producing such position-sensitive detectors. The subject of this paper is the detector technology developed at Lawrence Berkeley National Laboratory (LBNL) that enables the simple production of Ge-based gamma-ray detectors with fine spatial resolution. In particular, we describe the amorphous-semiconductor contact technology [2–9], its advantages, and the developmental work that remains to be done.

2. Amorphous-semiconductor contacts

A simple single-element Ge gamma-ray detector (see Fig. 1a) consists of a block of high-purity Ge material in

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which n+ and p+ impurity-doped electrical contacts have been fabricated on opposite sides of the block. The detector is operated as a fully depleted reverse-biased diode, and spectroscopy is performed by measuring the electron–hole pair charge generated by each gamma-ray interaction event within the detector. The standard contact technology for such a detector consists of a Li-diffused n+ contact and a B-implanted p+ contact. Both contact types are robust, can withstand high electric fields, and lead to low charge carrier injection.

To produce a position-sensitive detector for imaging applications, the electrical contacts on the detector are divided into segments as shown in Fig. 1b. This can be readily done on the B-implanted contact [10,11] but is problematic on the Li-diffused side because of the contact thickness and the continued Li diffusion into Ge at room temperature. Furthermore, the inter-contact surfaces for both contact types should be passivated to obtain long-term detector stability, thereby necessitating additional processing steps. An alternative technology capable of producing position-sensitive detectors is the amorphous-semiconductor contact developed at LBNL. With this technology (see Fig. 1c), the contacts are formed by first coating all surfaces of the Ge crystal with a thin film of high-resistivity amorphous semiconductor (typically Ge or Si). Metal layers in the desired pattern are then deposited on top of the amorphous layer to complete the contact fabrication. The physical contact area in such a detector is defined by this low-resistivity metallization. However, most of the important electrical properties of the contact structure are dictated by the amorphous-semiconductor layer and the amorphous-semiconductor to crystalline Ge interface. The advantages of this technology are (1) fabrication simplicity, (2) thin contact dead layers, (3) complete surface passivation, since amorphous Ge (a-Ge) layers are commonly used for Ge passivation, (4) fine achievable contact pitches, and (5) bipolar blocking contacts. Much of the remainder of this paper will focus on describing how the contacts function and the improvements needed to make this a more widely adopted contact technology.

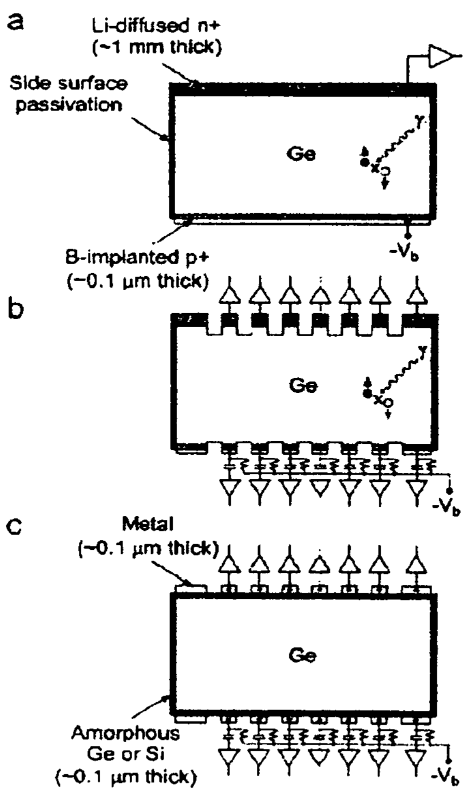

Fig. 1. Germanium-based gamma-ray detector configurations. (a) Conventional simple planar detector with Li-diffused anode and B-implanted cathode. (b) Position-sensitive detector produced using the conventional contact technologies. (c) Position-sensitive detector produced using the amorphous-semiconductor contact technology.

The amorphous-semiconductor contacts on Ge behave much like Schottky metal-semiconductor contacts with electron and hole barriers to charge injection typically equal to about half the bandgap energy of Ge. Consequently, the contacts can block the injection of both types of charge carriers, and the same contact can therefore operate with low leakage current under either bias polarity. This is in contrast to conventional impurity-doped contacts which block injection under only one bias polarity, and metal-Ge surface barrier contacts that typically block well only when negatively biased. The bipolar blocking behavior is demonstrated in Fig. 2 where the leakage current from an a-Ge contact detector is plotted for both negative and positive detector biases. Under either detector polarity, one of the a-Ge contacts is positively biased and

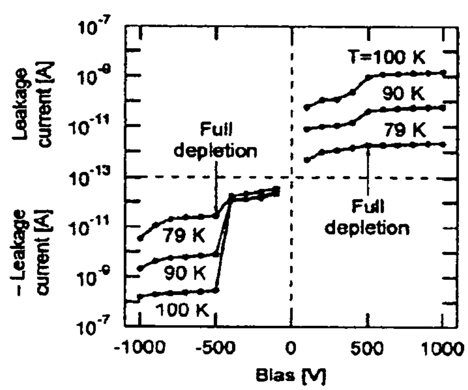

Fig. 2. Measured leakage current plotted as a function of bias voltage at three different temperatures for a p-type Ge detector fabricated with a-Ge electrical contacts (a-Ge/p-type Ge/a-Ge device). The detector thickness and active area were 1 cm and 1.7 cm², respectively.

the other negatively biased, yet low leakage is obtained at typical operating temperatures.

The electron or hole energy barrier to charge injection is an important property of a contact that dictates the level of charge injected into the detector which in turn can impact energy resolution if excessive. To determine the electron barrier of an amorphous contact, we fabricate a detector consisting of p-type Ge with a Li n+ contact on one side and the amorphous contact to be evaluated on the other. Under reverse bias, the depletion within this detector begins at the Li contact and, as the bias is increased, extends towards the amorphous contact. At full depletion, the field penetrates to the amorphous contact, and a step increase in the leakage current is observed that is a result of electron injection at the amorphous contact. By measuring this step height as a function of temperature and fitting the data to a simple thermionic emission model [12], we are able to extract out the electron barrier. An example measurement from an n+/p-type Ge/a-Ge detector is given in Fig. 3a, and the barrier height extraction is shown in Fig. 4 plot (a). Similarly, an n-type Ge detector with a B-implanted p+ contact (or Pd metal-semiconductor contact) on one side and the amorphous contact on the opposite side can be used to determine the hole barrier of the amorphous contact. An example measurement from a Pd/n-type Ge/a-Ge detector is shown in Fig. 3b and the hole barrier height determination in Fig. 4 plot (b). From simple Schottky contact theory, the sum of the electron barrier and the hole barrier for a particular contact should equal the Ge bandgap energy. From Fig. 4, we see that the sum for this particular a-Ge contact is 0.68 eV and is reasonably close to the Ge bandgap energy (at the average measurement temperature of 135 K) of 0.72 eV.

The barrier heights of the amorphous-semiconductor contacts depend in part on the semiconductor used and the method by which they are deposited. This is an important tool that can be used to optimize detector performance. Our standard method to deposit the amorphous films is rf sputtering in pure Ar and Ar–H_2 gas mixtures. The addition of H_2 to the sputter gas produces a-Ge and a-Si films of substantially higher resistivities than those obtained with pure Ar sputtering and also impacts the barrier heights. A summary of the barrier heights measured for a few different types of amorphous-semiconductor contacts is given in Table 1 [13]. The data show that a-Ge sputtered in pure Ar (a-Ge (Ar)) produces electron and hole barriers of nearly the same value, which is approximately half of the Ge bandgap. If, for fabrication simplicity, a single contact process were used to produce all contacts on a detector, it would seem that the a-Ge (Ar) contact would be the best since it should lead to the lowest detector leakage. However, the resistivity of the a-Ge (Ar) can potentially be low enough to degrade energy resolution as a result of the Johnson noise associated with the low inter-contact resistance caused by the a-Ge (Ar) layer. The addition of H_2 to the sputter gas increases the a-Ge film resistivity by several orders of magnitude and solves this problem. In part, for this reason, we typically use a-Ge ($Ar+H_2$) to produce finely segmented detectors.

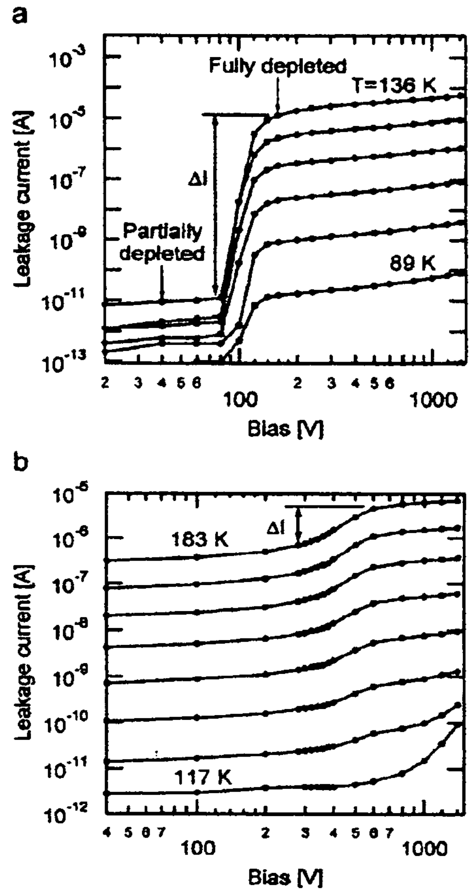

Fig. 3. Measured leakage current as a function of bias voltage for Ge detectors at various temperatures. (a) Detector with a configuration of Li diffusion/p-type Ge/a-Ge (Ar + 17.5% H_2). The detector thickness and area were 0.6 cm and 3.5 cm^2, respectively. (b) Detector with a configuration of Pd/n-type Ge/a-Ge (Ar + 17.5% H_2). The detector thickness and area were 0.6 cm and 3.1 cm^2, respectively.

Detectors produced with a-Ge (Ar + 17.5% H_2) contacts for both the positive and negative contacts operate with low leakage and good spectroscopic performance at temperatures near that of liquid nitrogen. If, however, the detector temperature is increased to about 90 K or above, the leakage current can be significant enough to degrade the detector energy resolution. The temperature dependence of the leakage current for an all a-Ge (Ar + 17.5% H_2) contact detector is shown in Fig. 5a. The leakage current step increase exhibited in the plots results from electron injection at the negative contact when full depletion is reached. As the data of Table 1 indicate, the addition of H_2 to the sputter gas has not only increased the a-Ge film resistivity, but it has also increased the hole

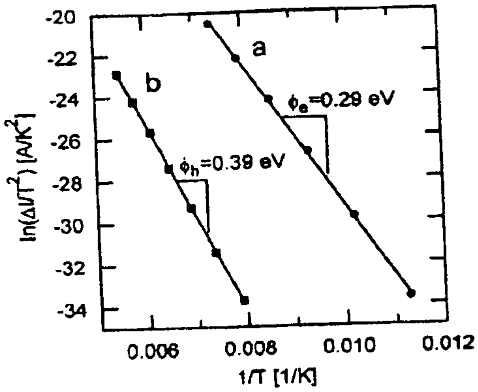

Fig. 4. Plot illustrating the barrier height extraction from the data of Fig. 3.

Table 1
Extracted barrier heights for amorphous semiconductor contacts on high purity Ge

Contact	ϕ_e (eV)	ϕ_h (eV)	$\phi_e+\phi_h$ (eV)	ρ (Ωcm)
a-Ge (Ar)	0.36	0.34	0.70	$\sim10^6$–10^8
a-Ge (Ar + 17.5% H_2)	0.29	0.39	0.68	$\sim10^{11}$
a-Si (Ar)	0.39	0.28	0.67	$\sim10^9$

The sum of the electron and hole barrier heights and film resistivities measured at 77 K are also listed.

barrier at the expense of the electron barrier. The reduced electron barrier is then the primary cause of the leakage in Fig. 5a. We have demonstrated that replacing the negative contact with the higher electron barrier a-Si contact substantially lowers the detector leakage at the higher temperatures. This is shown in Fig. 5b. Such a detector configuration is appropriate when higher operating temperatures are desired.

Germanium-based gamma-ray detectors with a-Ge contacts have successfully been produced for several prototype imaging instruments [4,14–17]. A typical configuration for these detectors is the orthogonal-strip geometry with strip pitches between 1 and 2 mm and detector volumes as large as 160 cm^3. Excellent energy resolution and three-dimensional position detection [6,7,18] are achieved with these detectors. We have also demonstrated the fine-electrode segmentation capability of the contacts by fabricating strip detectors with pitches down to 50 μm.

3. Future improvements

Despite the substantial success achieved with Ge-based detectors fabricated using amorphous-semiconductor contacts, issues remain to be resolved before the full potential of the devices will be realized in large-scale instruments. These issues include excessive leakage at temperatures significantly above that of liquid nitrogen, leakage current degradation with temperature cycling, and charge collection to inter-contact surfaces. The excessive leakage current issue was discussed in the previous section and, as we have shown, can be addressed through the development and optimization of the a-Ge/Ge/a-Si detector configuration and other similar structures.

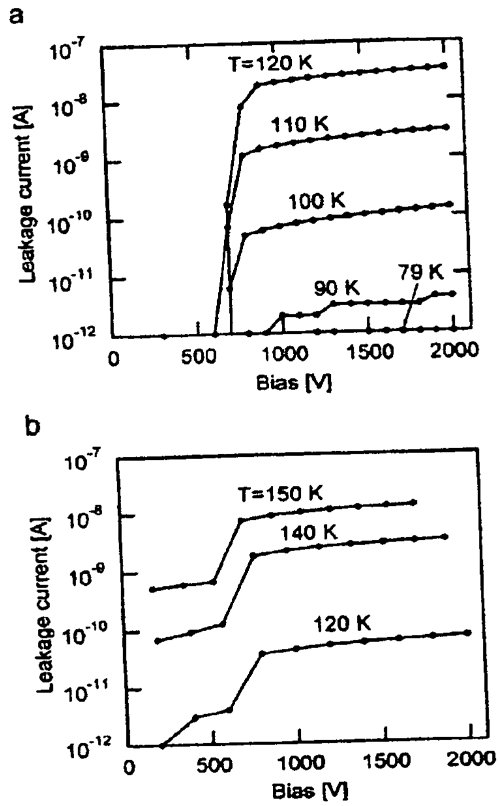

Fig. 5. Measured leakage current as a function of bias voltage for Ge detectors at various temperatures. (a) Detector with a configuration of a-Ge (Ar + 17.5% H_2)/p-type Ge/a-Ge (Ar + 17.5% H_2). The detector thickness and active area were 1 cm and 1 cm^2, respectively. (b) Detector with a configuration of a-Ge (Ar + 17.5% H_2)/p-type Ge/a-Si (Ar + 7% H_2). The detector thickness and area were 1 cm and 1 cm^2, respectively.

Cycling the temperature of an amorphous-contact Ge detector from cryogenic temperatures to room temperature and then back to a low temperature again typically causes the leakage current of the detector to increase at the operating temperature. Such temperature cycling is unavoidable in the detector evaluation and instrument assembly process. The gradual increase in the leakage caused by this cycling can ultimately lead to degraded energy resolution. We have found that the extent of this degradation is dependent on the parameters used during the sputter deposition of the amorphous-semiconductor layer (temperature, power, sputter gas mixture and pressure) and can be substantially reduced through

judicious selection of the parameters. However, additional work in this area is necessary to optimize the sputter deposition process for improved cycling behavior, verify the reproducibility of the results, and determine the robustness of the improved process when applied to large-area segmented detectors.

When charge from a gamma-ray interaction event is collected to the surfaces separating adjacent contacts rather than to the contacts themselves, a deficit in the measured charge results that can degrade spectroscopic performance [5–7]. The extent of this incomplete charge collection is affected by the nature of the amorphous-semiconductor layer on the inter-contact surfaces. Several possible approaches exist to lessen or eliminate this problem and include (1) optimizing the amorphous layer and surface processing so that charge accumulation inhibits the collection of signal charges at the inter-contact surface [7], (2) minimizing the area of inter-contact surfaces at the price of greater inter-contact capacitance and, consequently, electronic noise, (3) etching away the amorphous-semiconductor surface layer between contacts [8], (4) making use of field-shaping electrodes [6,7], and (5) signal processing to correct for the charge loss. Further work in this area is required to determine the effectiveness and reliability of each approach as well as to identify any shortcomings so that the best solutions can be applied to future detectors.

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